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Alternative Fuels DISI Engine Research

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Overall Objectives

Provide the science-base needed by industry to understand:

- How emerging alternative fuels impact highly efficient DISI light-duty engines being developed by industry.
- How engine design and operation can be optimized for most efficient use of future fuels.

Fiscal Year (FY) 2015 Objectives

- Work towards developing a conceptual understanding of stratified SI combustion that incorporates the effects of fuel on combustion stability and exhaust-emissions formation.
- Identify and explain combinations of fuel characteristics and operating strategies that enable stable and efficient well-mixed lean SI operation.

FY 2015 Accomplishments

- Based on PIV and flame imaging, developed conceptual descriptions of both the spray-swirl interactions and flame-spread patterns that act to stabilize stratified combustion.
- Examination of effects of fuel blend (E0 to E30) on boosted, stratified operation with double injections.
- Quantified control authority over the ignition process, for both advanced multi-pulse (MP) transient plasma ignition and with partial fuel stratification (PFS).
- Compared lean and dilute stability limits and fuel-efficiency gains for E30, E85 and gasoline, using enhanced ignition to ensure repeatable end-gas autoignition for high combustion efficiency of ultra-lean deflagration-based SI operation.
- These accomplishments address one of the barriers identified by DOE VT: Inadequate data for fuel property effects on combustion and engine efficiency optimization.

Future Directions

- Expand conceptual model of swirl-spray stabilization mechanism to include double injections of E0 - E30 fuels for boosted stratified operation.

- Continue examination of well-mixed lean or dilute SI operation while quantifying the relevance of RON and MON for fuel reactivity under ultra-lean conditions.
- Incorporate new fuel components and blends in coordination with the Optima inititative
- Refine PFS technique to allow the use of a smaller pilot-fuel quantity and apply PFS to examine fuel effects on limits of ultra-lean SI combustion.

Introduction

Climate change and the need to secure energy supplies are two reasons for a growing interest in engine efficiency and alternative fuels. This project contributes to the science-base needed by industry to develop highly efficient DISI engines that also beneficially exploit the different properties of alternative fuels. Our emphasis is on lean operation, which can provide higher efficiencies than traditional non-dilute stoichiometric operation. Since lean operation can lead to issues with ignition stability, slow flame propagation and low combustion efficiency, we focus on techniques that can overcome these challenges. Specifically, fuel stratification is used to ensure ignition and completeness of combustion but has soot- and NO_x- emissions challenges. For ultra-lean well-mixed operation, turbulent deflagration can be combined with controlled end-gas autoignition to render mixed-mode combustion that facilitates high combustion efficiency. However, the response of both combustion and exhaust emissions to these techniques depends on the fuel properties. Therefore, to achieve optimal fuel-economy gains, the engine combustion-control strategies must be adapted to the fuel being utilized.

Approach

The Alternative Fuels DISI Engine Lab at Sandia houses an engine that is capable of both performance testing and in-cylinder optical diagnostics. First, to characterized fuel-efficiency and emissions behavior, performance testing with an all-metal engine configuration is conducted over wide ranges of operating conditions and alternative-fuel blends. Second, in-cylinder processes are examined with high-speed optical diagnostics, including advanced laser-based techniques. Computer modeling also provides insight into the governing combustion fundamentals. The combination of performance testing, exhaust-emissions measurements, optical diagnostics, and modeling allows building a comprehensive science-base.

Results

In the following, examples of accomplishments during FY2015 are presented.

<u>Stratified-Charge Operation</u> – experiments show that intake-generated swirl promotes stable stratified combustion for both E30 and gasoline. To clarify the mechanism through which swirl stabilizes combustion, the in-cylinder flow was examined with particle image velocimetry for both swirling and non-swirling flows. The measurements show that swirl makes the flow patterns of individual cycles more similar to the ensemble-averaged cycle. Figure 1 quantifies this effect statistically through a “flow similarity” parameter (R_p), and shows that operation with swirl increases R_p from 0.77 to 0.90 at the time of spark ignition - reducing IMEP variability from 3.5% to 1.4%.

Research during FY2015 reveals that the interaction of the eight fuel sprays with the swirling gas flow strongly contributes to the flow stabilization at the time and location of the spark, as described conceptually in Fig. 2. Flow measurements in both a horizontal and a vertical plane reveal that the fuel sprays displace low angular-momentum gas downwards. In the wake of the spray, higher angular momentum gas from larger radii flows inward and increases its rotation rate due to conservation of momentum. This process creates a strong and very repeatable vortex near the spray centerline at the time of spark, as demonstrated by the vector fields on the right-hand-side of Fig. 1. It should be noted that the optimal spark timing for both gasoline and E30 coincides with the end of injection, so these descriptions apply to both fuels.

The increased flow similarity stabilizes the combustion process by reducing variability in both the ignition event and in the flame spread throughout the remaining charge. Analysis of a large number of flame images reveals that the flame-spread patterns are very repeatable for operation with swirl, as described by the schematic in the left-hand side of Fig. 3. It shows that the strong vortex near the center of the combustion chamber promotes flame spread in the 6 o'clock direction. This avoids the occurrence of slow-burning cycles that may develop into partial burns. In contrast, the flow fields without swirl in the left-hand side of Fig. 1 show no evidence of such a stabilizing vortex. Moreover, the single-cycle example without swirl is quite different from the average flow field, consistent with the observed higher combustion variability. Without swirl, the flame spread is occasionally very delayed in the 6 o'clock direction, as depicted on the right-hand side of Fig. 3. This causes both combustion inefficiency and lower IMEP.

Based on this understanding of swirl-spray interactions and flame-spread patterns, combustion engineers can optimize injector and flow parameters to maximize combustion stability and enable high-efficiency operation. Moreover, the experiments show that the swirl-spray interaction and combustion-stability characteristics are very similar for gasoline and mid-level ethanol blends, indicating that advanced stratified-charge combustion systems can be developed to accommodate potential future fuel changes.

<u>Lean well-mixed operation</u> – Lean or dilute operation can improve the thermal efficiency, but the fuel-economy gains depend on several factors, including fuel type, dilution type, and intake temperature. This is exemplified in Fig. 4. For both E30 and gasoline, there are two lean ϕ-sweeps where air is used as the oxidizer ([O_2] = 20.9%), and two stoichiometric dilute ϕ_m- sweeps where [O_2] is reduced by the addition of N_2. (To aid comparisons of the lean and dilute data sets, a mass-based equivalence ratio, ϕ_m, is used as a measure of the chemical energy per reactant mass, regardless of type of diluent [1].) For each type, two different intake temperatures are used; 30°C or 100°C (*i.e.* heated). In Fig. 4c, it can be seen that the fuel economy (FE) of gasoline improves by roughly 20% for ϕ = 0.52 - 0.55. In contrast, the best FE improvement is only 17% for E30, shown in Fig. 4a. This difference can be attributed to the higher octane numbers of E30, which make it harder to achieve mixed-mode combustion for this operating point. This is illustrated in Fig. 5, which plots the ensemble-averaged AHRR traces for gasoline, E30, and E85 operated lean with heated intake and ϕ = 0.55. The three fuels have nearly identical deflagration-based AHRR until TDC, at which point the AHRR of gasoline deviates due to the onset of mild end-gas autoignition. As a result, the AHRR of gasoline keeps rising until a peak has been reached at 10°CA, and falls off rapidly thereafter. Due to this change of the AHRR profile, less heat is released during the later part of expansion stroke and this explains the larger gain of η_{th}. Both E30 and E85 display a slow burn-out process with substantial heat being released after 20°CA, making the conversion of heat to work less efficient.

Compared to heated lean operation, Figs. 4 shows that the other modes of operation provide less η_{th} benefit, and are also more limited by onset of IMEP variability. Stoichiometric dilute operation offers the smallest η_{th} benefit for either fuel, with roughly 10% FE gain for heated dilute and 7% for non-heated dilute. The poor performance of dilute operation is largely explained by its slow early flame development and slower overall heat release. To speed up the dilute combustion process, end-gas autoignition can be utilized. However, the regular spark system does not provide sufficient control authority to accomplish stable dilute mixed-mode combustion. Therefore, the more powerful MP ignition system [2] was used for both E30 and gasoline. Figure 6b shows that gasoline and E30 exhibit nearly identical AHRR profiles when CA50 is advanced to near TDC, with a distinct second peak around 10°CA and a crisp end of combustion. Furthermore, Fig. 6a indicates that the autoignition temperatures are practically identical for the two fuels at this operating condition. This is remarkable, given that the legend of Fig. 6a indicates that RON is 7 units higher for E30, and MON is 2 units higher. At the operating conditions of Fig. 6, the effective octane index (OI) [3] must be identical for the two fuels. This implies that this particular operating point is "beyond MON". These and other results motivate future work to assess the relevance of RON and MON for advanced combustion modes.

Conclusions

- The Alternative Fuels DISI Engine Lab at Sandia contributes to the science-base needed by industry to take full advantage of future fuels in advanced SI engines.
- Conceptual models and descriptions of stratified SI combustion have been developed that explain the mechanisms whereby intake-generated swirl acts to stabilize combustion.
- E30 and gasoline show very similar combustion behavior for stratified operation, suggesting that stratified-charge combustion systems can be made fully compatible with mid-level ethanol blends.
- For well-mixed operation, a comparison of E30, E85 and gasoline reveals that lean operation with intake-air preheating provides higher fuel-economy gains than stoichiometric dilute operation. The inferior performance of dilute operation is partly caused by slower combustion caused by an EGR-induced reduction of the reactant [O_2].
- For stoichiometric dilute operation with intake heating, a multi-pulse ignition system can be used to induce mixed-mode combustion, providing faster combustion and higher efficiency. For such operation, differences in RON and MON become irrelevant, with E30 and gasoline showing identical autoignition temperatures and AHRR profiles.

References

1. M. Sjöberg and W. Zeng, "Combined Effects of Fuel and Dilution Type on Efficiency Gains of Lean Well-Mixed DISI Engine Operation with Enhanced Ignition and Intake Heating for Enabling Mixed-Mode Combustion", accepted for SAE Congress 2016.
2. M. Sjöberg, W. Zeng, D. Singleton, J.M. Sanders, and M.A. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 DISI Engine Operation", SAE Int. J. Engines 7(4):1781-1801, 2014.
3. Kalghatgi, G., "Fuel Anti-Knock Quality - Part I. Engine Studies," SAE Technical Paper 2001-01-3584, 2001.

FY 2015 Publications/Presentations

1. W. Zeng, M. Sjöberg, D.L. Reuss and Z. Hu, "The Roles of Spray and Flow for Spray-Guided Stratified-Charge DISI Combustion", 17th Annual Conference of ILASS-Asia, Oct 2014.
2. M. Sjöberg, W. Zeng, D. Singleton, J.M. Sanders and M.A. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation", presented at 2014 SAE International Powertrain, Fuels and Lubricants Meeting, and published in SAE Int. J. Engines 7(4):1781-1801, 2014.
3. W. Zeng, M. Sjöberg, and D.L. Reuss, "Combined Effects of Flow/Spray Interactions and EGR on Combustion Variability for a Stratified DISI Engine", published in Proceedings of the Combustion Institute, 35(3):2907-2914, 2015.

4. W. Zeng, M. Sjöberg and D.L. Reuss, "PIV Examination of Spray-Enhanced Swirl Flow for Combustion Stabilization in a Spray-Guided Stratified-Charge DISI Engine", published in International Journal of Engine Research, 16(3):306-322, 2015.
5. M. Sjöberg, W. Zeng and Z. Hu, "Efficiency Gains for Various Combinations of Enhanced Ignition, Intake Heating and Fuel Type for Lean or Dilute DISI Engine Operation", presented at Advanced Engine Combustion Review Meeting, Feb 2015.
6. W. Zeng, M. Sjöberg and Z. Hu, "Utilizing Intake Boost and Double Injections for Enhanced Stratified-Charge DISI Operation", presented at Advanced Engine Combustion Review Meeting, Feb 2015.
7. M. Sjöberg, "Efficiency Benefits of Lean or Dilute Well-mixed DISI Engine Operation with Advanced Ignition, Intake Heating and Various Fuel Types", presented at SAE 2015 High-Efficiency IC Engine Symposium.
8. W. Zeng, M. Sjöberg, D.L. Reuss and Z. Hu, "The Role of Spray-Enhanced Swirl Flow for Combustion Stabilization in a Stratified-Charge DISI Engine", presented at SAE Congress, April 2015.
9. M. Sjöberg, "Advanced Lean-Burn DI Spark Ignition Fuels Research", presented at the 2015 Annual Merit Review and Peer Evaluation Meeting, June 2015.
10. Y. Yang, J.E. Dec, M. Sjöberg, and C. Ji, "Understanding fuel anti-knock performances in modern SI engines using fundamental HCCI experiments", published in Combustion and Flame, 162(10):4008-4015, 2015.
11. M. Sjöberg, W. Zeng, Z. Hu, and M. Mehl, "Examination of Gasoline, E30 and E85 for Well-mixed Lean or Dilute DISI Engine Operation", presented at AEC Program Review Meeting, Aug 2015.
12. W. Zeng and M. Sjöberg, "Comparing Single- and Double-Injection Strategies for Spray-Guided Stratified-Charge DISI Combustion", presented at AEC Program Review Meeting, Aug 2015.

Acronyms

ϕ	Fuel/Air Equivalence Ratio
ϕ_m	Mass-based Fuel/Air Equivalence Ratio
η_{th}	Thermal Efficiency
$[O_2]$	mole fraction of oxygen (in intake)
°CA	Crank Angle Degrees
AEC	Advanced Engine Combustion
AHRR	Apparent Heat-Release Rate
AKI	Anti-knock Index
DISI	Direct-Injection Spark Ignition
DOE	Department of Energy
E30	Fuel blend with 30% ethanol and 70% gasoline by volume.
E85	Fuel blend with 85% ethanol and 15% gasoline by volume.
FPT	First-Pulse Timing
FY	Fiscal Year
IMEP	Indicated Mean Effective Pressure
NO_x	Nitrogen Oxides
PIV	Particle Image Velocimetry
rpm	Revolutions per minute
SI	Spark Ignition
$T_{end\text{-}gas}$	End-gas Reactant Temperature
T_{in}	Intake Temperature
VT	Vehicle Technologies

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Figures

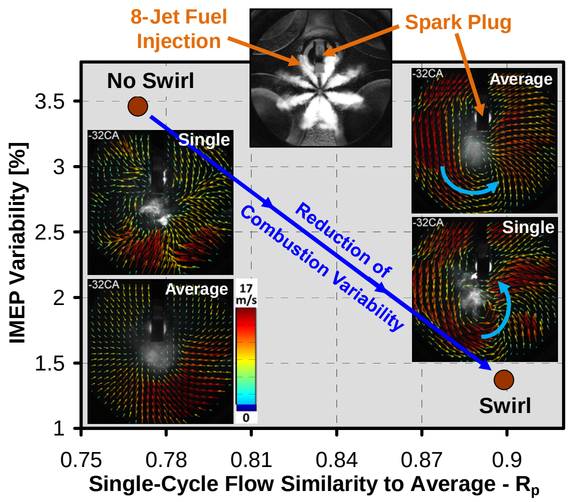

Figure 1. [Effect of swirl on combustion and flow variability for stratified-charge operation.]

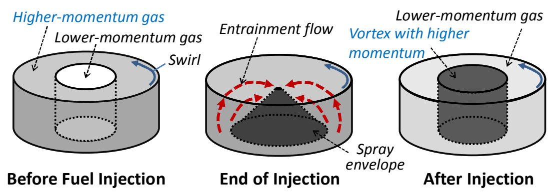

Figure 2. [Conceptual model of spray-swirl interactions that create a repeatable vortex near the spark plug for stratified-charge operation].

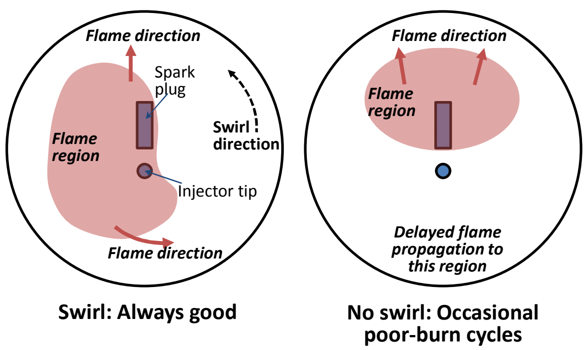

Figure 3. [Description of flame spread for stratified-charge operation with and without intake-generated swirl].

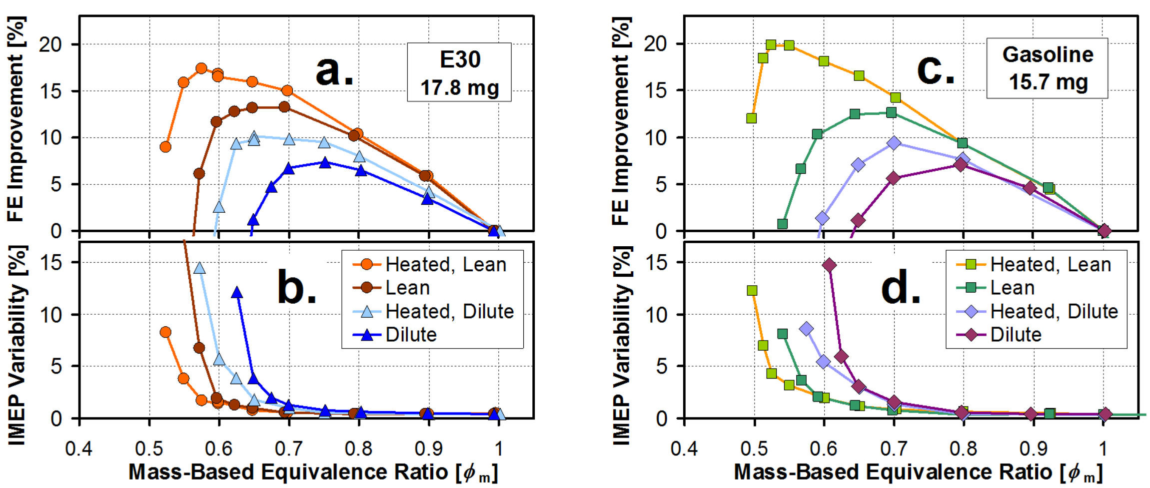

Figure 4. [Comparison of E30 and gasoline for well-mixed lean or dilute operation at 1000 rpm. a & c show improvement of fuel economy relative $\phi = 1$ operation. b & d show $IMEP_n$ variability.]

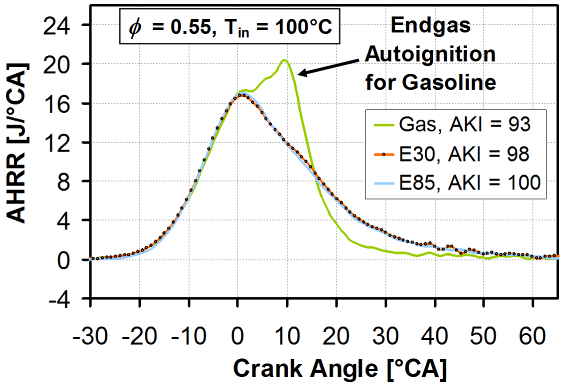

Figure 5. [Comparison of heat-release rate for heated lean operation with gasoline, E30 and E85.]

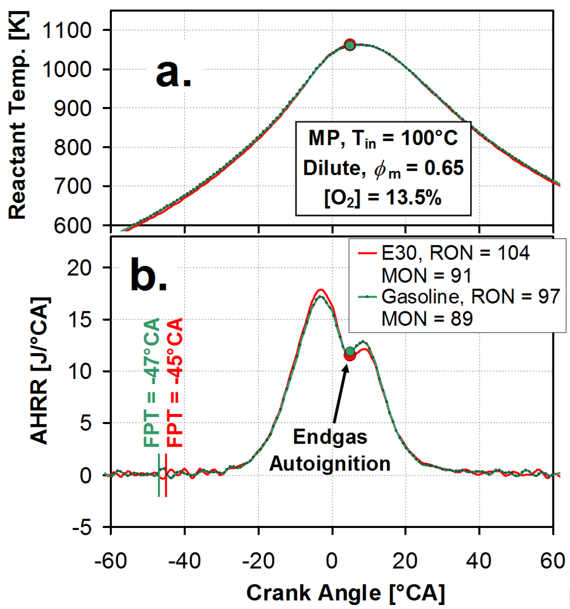

Figure 6. [The use of MP ignition to induce stable stoichiometric dilute mixed-mode combustion for both E30 and gasoline. a) estimated $T_{end\text{-}gas}$, b) AHRR.]